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MIMO Techniques for Carrierless Amplitude and Phase modulation in Visible Light Communication

Author 1 and Author 2

Abstract—In this letter, multiple-input multiple-output (MIMO) techniques are proposed to improve the spectral efficiency and bit error rate (BER) performance of the conventional carrierless amplitude and phase modulation (CAP) in visible light communication (VLC). Analytic frameworks for both multiplexing and diversity MIMO techniques are developed for CAP. The analytical expressions in line-of-sight (LOS) propagation are validated via simulation. A precoding technique is further applied to improve the power efficiency of the multiplexing scheme resulting in an SNR gain of 28.5 dB.

Index Terms—Visible light communication (VLC), multiple-input multiple-output (MIMO), carrierless amplitude and phase modulation (CAP), precoding technique.

I. INTRODUCTION

The white LEDs employed in VLC are primarily designed for illumination purposes and as such have small modulation bandwidth in the order of tens of MHz [1]. This necessitates the application of bandwidth enhancing schemes such as the use of complex modulation schemes and equalization techniques to enhance the spectral efficiency of VLC links.

Carrierless amplitude and phase modulation (CAP) is one of the spectral efficient modulation techniques that are employed in VLC systems to improve bandwidth efficiency. The main attractions for CAP are its ease of implementation and unique features that make it specially suitable for VLC applications. Unlike its Quadrature Amplitude Modulation (QAM) counterpart, CAP has a simpler implementation as it uses a pair of orthogonal filters to eliminate the need for carrier modulation. Additionally, while CAP has similar spectral efficiency as optical orthogonal frequency division multiplexing (OFDM), it has been shown to have a lower peak-to-average-power ratio (PAPR) and a better BER and data rate performance in VLC links when compared to optical OFDM [2].

Despite the simple implementation of CAP, its performance is affected by the limited modulation bandwidth of the white LEDs employed in VLC. As a result, the main focus in the literature is the designing of various equalization techniques to improve the throughput of CAP in VLC applications [3]. However, these equalization techniques significantly increase the complexity of the resulting system. Therefore, a novel approach is proposed in this letter using spatial domains to improve the spectral efficiency and BER performance of CAP while maintaining its low complexity transceiver.

Multiple LEDs are often deployed to achieve sufficient illumination due to the limited luminous flux of the individual LED. The availability of these multiple LEDs have been exploited in the literature to achieve improved throughput using MIMO techniques [1]. Therefore, this letter exploits the

use of spatial domains to realise diversity and multiplexing gain for CAP modulation scheme in VLC applications. Spatial multiplexed CAP (SM_{ux}-CAP) which simultaneously transmit streams of independent CAP signals through multiple LEDs, is developed to realise significant improvement in the data rate of conventional CAP. While repetitive coded CAP (RC-CAP), with parallel transmission of the same CAP signal over multiple LEDs, is proposed to improve the BER performance of CAP through spatial diversity. The proposed techniques are novel implementations of CAP in MIMO systems and demonstrate its potential as a suitable modulation technique for VLC applications.

The main contributions of this letter are therefore summarized as follows: 1.) MIMO techniques are developed for improved data rate and BER performance of the conventional CAP; 2.) the BER analysis of the proposed schemes are derived and verified via simulation; and 3.) a precoding technique is applied to improve the power efficiency of the proposed MIMO scheme. The rest of the paper is organized as follows: the system model for CAP is presented in Section II. The BER analysis of the proposed MIMO techniques are derived in Section III while Section IV discusses the simulation and analytical results. Section V concludes the paper.

II. CAP SYSTEM MODEL

In order to generate CAP signal, the information bits are mapped to an M -QAM symbol and upsampled to match the system sampling rate [3]. The upsampled symbol is then separated into its real and imaginary components before being respectively fed into the in-phase and quadrature transmit filters. These transmit filters form a pair of orthogonal filters and are realised as the product of a root raised cosine filter (RRC) and sine and cosine waves [3]. The output of the filters are added together with a suitable DC bias to realise a unipolar signal. The resulting signal is then sent over the VLC channel by modulating it on the radiated intensity of the transmitting LED. The radiated optical signal, $s(t)$, can thus be written as:

$$s(t) = \kappa(\beta x(t) + x_{dc}) \quad (1)$$

where κ is the electrical to optical conversion coefficient, β is the modulation index and x_{dc} is the suitable DC bias. The CAP signal, $x(t)$, is expressed as:

$$x(t) = \sum_{n=-\infty}^{\infty} [a_n p(t - nT) - b_n \tilde{p}(t - nT)] \quad (2)$$

where $p(t)$ and $\tilde{p}(t)$ are, respectively, the real and imaginary transmit orthogonal filters while T is the symbol duration.

Considering an optical channel with a fixed LOS configuration and path loss h , the received electrical signal

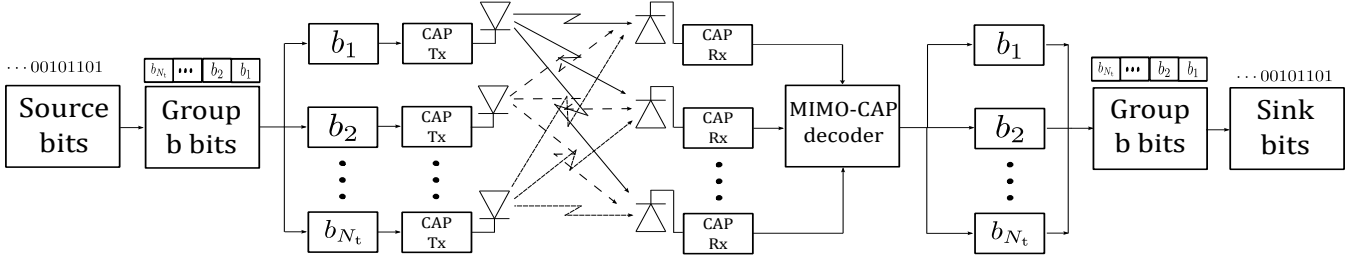


Fig. 1: The schematic block diagram of the MIMO CAP transceiver.

at the output of the PIN photodiode (PD), with DC bias suppressed, is expressed as:

$$y(t) = \Re h \beta \kappa x(t) + n(t) \quad (3)$$

where \Re represents the responsivity of the photodiode and $n(t)$ is the sum of ambient and thermal noise at the receiver. The noise is modelled as additive white Gaussian noise (AWGN) with zero mean and double-sided power spectral density, $N_0/2$. The received electrical signal is then passed to the CAP demodulator to recover the transmitted information bits.

III. BER PERFORMANCE ANALYSIS FOR MIMO CAP

The received electrical signal in (3) can be written, for an $N_r \times N_t$ MIMO configuration shown in Fig. 1, as:

$$\mathbf{y} = \Re h \beta \kappa \mathbf{H} \mathbf{x} + \mathbf{n} \quad (4)$$

where \mathbf{y} is an $N_r \times 1$ received signal vector, \mathbf{H} is an arbitrary $N_r \times N_t$ channel matrix with component \mathbf{h}_{n_r} representing the column vector of channel gains at the n_r th receiver, \mathbf{x} is an $N_t \times 1$ transmitted vector and \mathbf{n} is an $N_r \times 1$ noise components. Both N_t and N_r represent the number of transmitting LEDs and the number of receiving photodiodes, respectively.

A. CAP with Spatial Multiplexing (SM_{ux}-CAP)

For an SM_{ux}-CAP, at each transmitting instant, the incoming information bits are grouped into blocks of b bits as shown in Fig. 1 where $b = N_t \log_2 M$ and M represents the constellation size of an M -QAM scheme. The block of b bits is then divided into parallel streams, each of $\log_2 M$ bits, that are simultaneously passed into CAP modulators. The outputs are then sent over the VLC channel. In this way, N_t streams of independent CAP signals, each conveying $\log_2 M$ bits, are simultaneously transmitted resulting in total transmission of $N_t \log_2 M$ bits per symbol duration. Thus, SM_{ux}-CAP improves the bandwidth efficiency of the conventional CAP by a factor of N_t . At the n_r th receiver, given that symbol \mathbf{x}_m has been transmitted, the received electrical signal can be expressed as:

$$y_{n_r}(t) = r_{n_r}^m(t) + n_{n_r}(t) \quad n_r = 1, 2, \dots, N_r \quad (5)$$

where $r_{n_r}^m(t) = \Re h \beta \kappa \mathbf{h}_{n_r}^T \mathbf{x}_m(t)$. Hence, the output of SM_{ux}-CAP demodulators is written as:

$$\mathbf{y} = \mathbf{r}^m + \mathbf{n} \quad (6)$$

where y_{n_r} , $r_{n_r}^m$ and n_{n_r} are the components of vectors \mathbf{y} , \mathbf{r}^m and \mathbf{n} , respectively. The optimum SM_{ux}-CAP detector decides on the estimated symbol using Maximum Likelihood (ML) detection criterion [4, p. 242–247]. This is because

the $\{\mathbf{x}_m\}_{m=1}^{M^{N_t}}$ are equiprobable with $p(\mathbf{x}_m) = 1/M^{N_t}$. Thus, the SM_{ux}-CAP optimum detector decides on the \mathbf{x}_m that maximizes the joint probability density function (PDF) of \mathbf{y} conditioned on \mathbf{r}^m as:

$$\hat{\mathbf{x}}_m = \arg \max_m p(\mathbf{y}, \mathbf{r}^m) \quad (7)$$

where the conditional PDF, given the AWGN corrupted channel, is expressed as:

$$p(\mathbf{y}, \mathbf{r}^m) = \frac{1}{(2\pi N_0)^{N_r/2}} \exp \left[\frac{-1}{2N_0} \|\mathbf{y} - \mathbf{r}^m\|_F^2 \right] \quad (8)$$

where $\|\cdot\|_F$ is the Frobenius norm. The ML detection criterion reduces to finding the \mathbf{x}_m that results in the minimum Euclidean distance, i.e.

$$\hat{\mathbf{x}}_m = \arg \min_m D(\mathbf{y}, \mathbf{r}^m) \quad (9)$$

and the distance metrics is given by:

$$D(\mathbf{y}, \mathbf{r}^m) = \|\mathbf{y} - \mathbf{r}^m\|_F^2 \quad (10)$$

In the case of correct decision, the decision metrics is given as

$$D(\mathbf{y}, \mathbf{r}^m) = \|\mathbf{n}\|_F^2 \quad (11)$$

otherwise,

$$D(\mathbf{y}, \tilde{\mathbf{r}}^m) = \|\mathbf{r}^m - \tilde{\mathbf{r}}^m + \mathbf{n}\|_F^2 \quad (12)$$

Therefore, the pairwise error probability (PEP) of SM_{ux}-CAP, which is defined as the probability that the SM_{ux}-CAP detector decides in favour of vector $\tilde{\mathbf{x}}$ given that \mathbf{x} has actually been transmitted, can be obtained as:

$$\begin{aligned} PEP_{\text{SM}_{ux}\text{-CAP}} &= p(\mathbf{x} \rightarrow \tilde{\mathbf{x}} | \mathbf{H}) \\ &= p(D(\mathbf{y}, \mathbf{r}^m) > D(\mathbf{y}, \tilde{\mathbf{r}}^m)) \\ &= Q \left(\sqrt{\frac{(\Re h \beta \kappa)^2 T}{2N_0}} \|\mathbf{H}(\mathbf{x}_m - \tilde{\mathbf{x}}_m)\|_F^2 \right). \end{aligned} \quad (13)$$

An upper bound BER expression, shown in (14), is then derived for SM_{ux}-CAP from (13) by considering all possible M^{N_t} signal combinations using the union bound technique [4, p. 261–262]. The $N_H(b_m, \tilde{b}_m)$ in (14) represents the number of bit in error when the receiver decides for the symbol $\tilde{\mathbf{x}}_m$ instead of the transmitted symbol \mathbf{x}_m .

B. CAP with Repetitive Coding (RC-CAP)

Repetitive coding is a MIMO technique in which the same symbol is simultaneously transmitted over multiple LEDs. This results in full transmit diversity of N_t in optical MIMO systems employing IM/DD approach. For RC-CAP, since

$$BER_{SM_{ux}-CAP} \leq \frac{1}{M^{N_t} \log_2(M^{N_t})} \sum_{m=1}^{M^{N_t}} \sum_{\tilde{m}=1}^{M^{N_t}} N_H(b_m, \tilde{b}_m) Q \left(\sqrt{\frac{(\Re \beta \kappa)^2 T}{2N_0}} \|\mathbf{H}(\mathbf{x}_m - \tilde{\mathbf{x}}_m)\|_F^2 \right). \quad (14)$$

$$BER_{RC-CAP} \leq \frac{1}{M \log_2(M)} \sum_{m=1}^M \sum_{\tilde{m}=1}^M N_H(b_m, \tilde{b}_m) Q \left(\sqrt{\frac{(\Re \beta \kappa)^2 T}{2N_0}} \sum_{n_r=1}^{N_r} \left(\sum_{n_t=1}^{N_t} h_{n_r n_t} \right)^2 |x_m - \tilde{x}_m| \right). \quad (15)$$

TABLE I: SIMULATION PARAMETERS FOR THE CHANNEL CONFIGURATION.

TX coordinates (m)	LED1 - (1.25,1.25,3), LED2 - (1.25,3.75,3), LED3 - (3.75,1.25,3), LED4 - (3.75,3.75,3)
\mathbf{H}_1 coordinates (m)	PD1 - (2.4,2.4,0), PD2 - (2.4,2.6,0), PD3 - (2.6,2.4,0), PD4 - (2.6,2.6,0)
\mathbf{H}_2 coordinates (m)	PD1 - (1.2,1.2,0), PD2 - (1.2,3.8,0), PD3 - (3.8,1.2,0), PD4 - (3.8,3.8,0)

$x_1 = x_2 = \dots = x_{N_t}$, $(\mathbf{x}_m - \tilde{\mathbf{x}}_m) = (x_m - \tilde{x}_m) \mathbf{1}_{N_t \times 1}$ where $\mathbf{1}_{N_t \times 1}$ is an $N_t \times 1$ vector that has all its entries to be unity. Thus, by algebraic manipulation, an upper bound for the BER of RC-CAP can be obtained from (14) as shown in (15).

However, the upper bound expression in (15) can be reduced to an approximation by noting that the argument of the Q -function is the transmitted SNR of a single-input single-output (SISO) system scaled by the summation of the channel gains. Therefore, using results such as in [5], an approximation for the BER of RC-CAP can be expressed as:

$$BER_{RC-CAP} \cong \frac{2(\sqrt{M} - 1)}{\sqrt{M} \log_2 \sqrt{M}} Q \left(\sqrt{\frac{3(\Re \beta \kappa)^2 T}{(M-1)N_0} \sum_{n_r=1}^{N_r} \left(\sum_{n_t=1}^{N_t} h_{n_r n_t} \right)^2} \right). \quad (16)$$

IV. NUMERICAL SIMULATION RESULTS AND DISCUSSIONS

In the results presented in this section, the electrical signal-to-noise ratio per bit is defined as $\gamma_b = \frac{(R\beta\kappa)^2 T}{\eta N_0}$ where $(R\beta\kappa)^2 T$ denotes the average transmitted electrical energy per symbol, E_s and $\mathbb{E}\{x^2(t)\} = 1$. The spectral efficiency, η , is $\log_2(M^{N_t})$ and $\log_2 M$ for SM_{ux} -CAP and RC-CAP, respectively. For a fair comparison, the emitted intensity from each transmitting LEDs has been scaled by a factor N_t to preserve the total transmit power for the two schemes, irrespective of the number of LEDs employed.

Two receiver position arrays are investigated for the proposed MIMO techniques. The first array, \mathbf{H}_1 , is realised by symmetrical arrangement of the PDs at the centre of the room. The second array is realised by direct placement of the PDs under the LEDs to maximize the received LOS signal. The channel gains corresponding to the two arrays are obtained using the ray tracing channel modelling technique in a room that is 3 m in height and 5 m in length and width [6]. The LED half angle, $\varphi_{1/2}$ is 60° , the Field of view of PD is 85° while the PD area, A_{PD} is given as 1 cm^2 . Other configuration

parameters are given in Table I. The channel gains, normalized such that the $\max\{h_{n_r n_t}\} = 1$, are given as:

$$\mathbf{H}_1 = \begin{bmatrix} 1.0000 & 0.8481 & 0.9194 & 0.9194 \\ 0.8481 & 1.0000 & 0.9194 & 0.9194 \\ 0.9194 & 0.9194 & 1.0000 & 0.8481 \\ 0.9194 & 0.9194 & 0.8481 & 1.0000 \end{bmatrix} \quad (17)$$

and

$$\mathbf{H}_2 = \begin{bmatrix} 1.0000 & 0.1675 & 0.3373 & 0.3373 \\ 0.1675 & 1.0000 & 0.3373 & 0.3373 \\ 0.3373 & 0.3373 & 1.0000 & 0.1675 \\ 0.3373 & 0.3373 & 0.1675 & 1.0000 \end{bmatrix} \quad (18)$$

The performance comparison of SM_{ux} -CAP and RC-CAP in a 4×4 MIMO set up with channel matrix \mathbf{H}_1 and $\eta = 8$ bits/s/Hz is presented in Fig. 2a. The results validate the derived analytical expressions for both SM_{ux} -CAP and RC-CAP as the various theoretical analysis curves show excellent agreement with the simulation results at the low BER region where meaningful communication takes place. The slight disagreement at $BER > 10^{-2}$ is however due to the union bound technique adopted in the analytical derivation. The SNR required for SM_{ux} -CAP to achieve the spectral efficiency of 8 bits/s/Hz, at a representative BER of 10^{-4} , is 48.5 dB for the channel configuration considered. This high SNR is due to the high similarity of the channel gains at this receiver position as evident from (17). Thus, SM_{ux} -CAP suffers BER degradation since it requires sufficient channel gain dissimilarity to separate the received signals. On the other hand, RC-CAP benefits from spatial diversity due to the high channel gains similarity. It achieves a representative BER of 10^{-4} at an SNR of 16 dB. The RC-CAP BER performance improvement due to similarity in the channel gains can be explained by the factor $\sum_{n_t=1}^{N_t} h_{n_r n_t}$ in (16). This factor increases with increasing channel gain similarity. This in turn increases the argument of the Q -function leading to a reduction in BER. Hence, it can be concluded that RC-CAP is a better choice than SM_{ux} -CAP in highly correlated channels. However, to achieve the same spectral efficiency as SM_{ux} -CAP with $M = 4$, RC-CAP requires a much higher constellation order of $M = 256$ which translates to higher PAPR at the transmitter [2]. The foregoing depicts the trade-off between multiplexing and diversity techniques for MIMO CAP in VLC applications in terms of BER performance, power penalty and spectral efficiency.

When the PDs are directly placed under the LEDs, the LOS gains become pronounced leading to highly dissimilar channel gains and a nearly diagonal channel matrix as shown in (18).

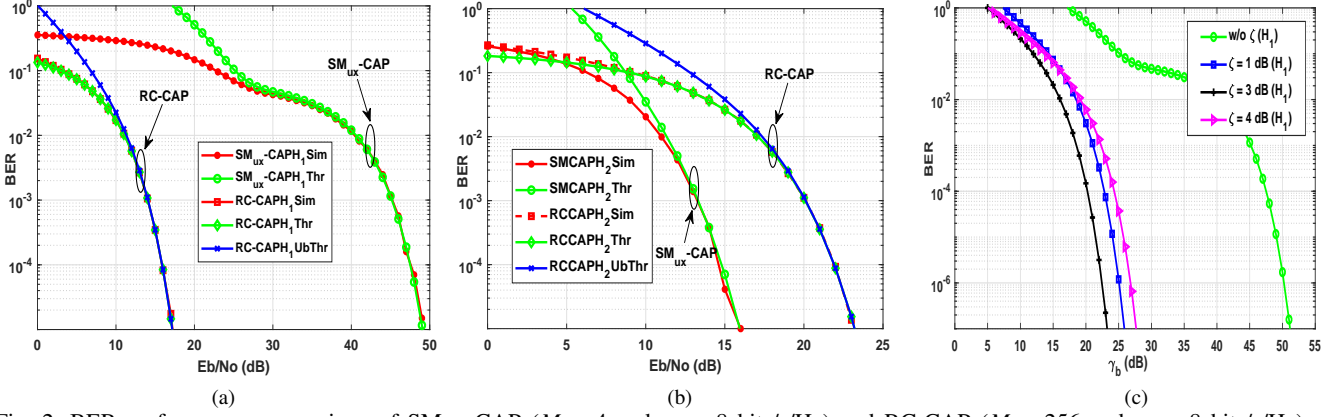


Fig. 2: BER performance comparison of SM_{ux} -CAP ($M = 4$ and $\eta = 8$ bits/s/Hz) and RC-CAP ($M = 256$ and $\eta = 8$ bits/s/Hz) using channel matrix (a) H_1 (b) H_2 ; (c) Improving the power efficiency of SM_{ux} -CAP using PFI precoding technique when channel gains are highly similar.

Sim : Simulation; Thr: Theory; UbThr: Upper bound Theory

Thus in Fig. 2b, RC-CAP loses some of its diversity gain as it achieves the representative BER of 10^{-4} at an SNR of 22 dB. This is a power penalty of 6 dB in comparison to the performance in H_1 and is due to the channel dissimilarity as previously discussed. However, SM_{ux} -CAP benefits from the channel dissimilarity to improve its performance by achieving the representative BER of 10^{-4} at an SNR of 14.5 dB. Thus, while still maintaining its spectral efficiency, SM_{ux} -CAP achieves a substantial SNR gain of 34 dB in comparison to its performance in H_1 . Thus, it can be inferred that SM_{ux} -CAP should be deployed in channels with dissimilar gains.

It is not always possible to achieve a dissimilar channel gains due to receiver mobility. In such cases where preliminary channel estimation shows highly similar channel gains, a precoding technique can be implemented to infuse dissimilarity and improve the power efficiency. Power factor imbalance (PFI) is a simple and very effective precoding technique. The PFI is implemented by scaling the emitted intensity from each LEDs with a weighting factor, δ_{n_i} . The weighting factor for each LED, derived such that the total transmit power is preserved, is given as:

$$\delta_{n_i} = \left(\frac{1}{N_t} \sum_{i=1}^{N_t} 10^{0.1(i-n_i)\zeta} \right)^{-1} \quad (19)$$

where ζ is a user-defined PFI in dB. It should be noted that the ζ implementation neither increases the total transmit power nor the complexity of the decoder. Also, the performance of RC-CAP is unaffected by ζ due to the preservation of the total transmit power and it is not necessary to apply ζ when the channel gains are similar. Hence, the effect of ζ is only shown on the performance of SM_{ux} -CAP in H_1 as depicted in Fig. 2c. It is seen that the ζ of 1 dB and 3 dB lead to substantial SNR gain of 26 dB and 28.5 dB, respectively when compared to the case of no ζ at the representative BER of 10^{-4} . This shows that ζ is an effective precoding technique for the improvement of the power efficiency of SM_{ux} -CAP. However, an optimum scaling factor is $\zeta = 3$ dB. Beyond 3 dB, ζ results in reduced SNR on the channels with smaller

gains which leads to performance degradation. This is reflected by the result of $\zeta = 4$ dB.

V. CONCLUSION

MIMO techniques have been proposed in this work to realise a low-complexity implementation of carrierless amplitude and phase modulation (CAP) with improved spectral efficiency and BER performance in visible light communication (VLC). It is found that RC-CAP is most suitable for highly correlated channels while SM_{ux} -CAP should be deployed in channels with dissimilar gains. A precoding technique is also implemented to improve the power efficiency of the MIMO scheme leading to an SNR gain of 28.5 dB. The resulting schemes represent a novel implementations of CAP in MIMO schemes and demonstrate its potential as a suitable modulation technique for VLC applications.

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